SUCTION PULSE DRILLING SYSTEM

RESULTS OF A PHASE I FEASIBILITY STUDY

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INTRODUCTION

Conventional rotary drilling is slowed by the confining pressure exerted by the column of mud in the borehole. The bottom hole pressure in a hole drilled for oil or gas is typically maintained at a value which is equal to, or slightly higher than the pore pressure of fluids (water, oil or natural gas) in the formation being drilled. The confining pressure of the mud increases the strength and plasticity of rock, reducing the efficiency of indentation and shear cutting (Kollé, 1996). The greatest effect of confining pressure occurs in shale, which also accounts for most of the rock encountered during drilling for oil and gas. Drilling experience has demonstrated that significant increases in drilling rate can be achieved by underbalanced drilling (in which the borehole pressure during drilling is smaller than the formation pressure). This is achieved by reducing the amount of weighting material added to the drilling mud or by using light-weight drilling fluids such as gas or foam to drill. The problem with underbalanced drilling is that the entire open section of the hole is subject to low pressure, which reduces borehole stability and increases the risk of a gas kick.

OBJECTIVE

An ideal drilling system would create a low-pressure region that is limited to the hole bottom while normal or overbalanced conditions are maintained above the bit to control formation fluids. The HydroPulse™ system shown in Figure 1 provides a means of generating intense cyclic suction pressure pulses that overcome the effects of borehole pressure and increase drilling penetration rate in deep formations. This system would be mounted on a conventional drill string and powered by mud hydraulics. The bottomhole assembly is compact and the system is compatible with downhole motors. The suction pulses could be used to enhance the penetration of conventional roller-cone, PDC or diamond bits. In many situations, such as horizontal drilling, it is difficult to apply a high mechanical thrust to the bit. The hydraulic thrust generated by a suction pressure pulse provides a means of drilling with minimal applied thrust. The suction pulse generator could also be used as a downhole seismic source or for a variety of workover operations such as removal of fines from damaged formations.

APPROACH

Drilling mud is normally pumped through a drill bit to remove cuttings from the hole bottom and transport them to the surface. When directed through high-speed flow courses, the mud flow contains significant kinetic energy, which can be converted into a suction pressure pulse by momentarily interrupting the flow with a valve as shown in Figure 2. This generates a suction pressure pulse downstream of the flow interruption. The suction pulse magnitude can be quite high because of the low compressibility of water-based drilling mud. The pulse results in an impulsive thrust on the bit at the same instant that the fluid pressure at the bit face is reduced. Suction pulse drilling results from the simultaneous combination of high indentation force on mechanical cutters and the reduced confining pressure.

The HydroPulse™ system employs a self-cycling poppet valve to generate the appropriate pulse magnitude and time history. The poppet valve design ensures that flow through the bit is maintained at a constant high velocity up to the instant that the valve closes. Instantaneously stopping the flow of water (or mud) in a closed conduit results in a suction pressure pulse downstream of the valve.

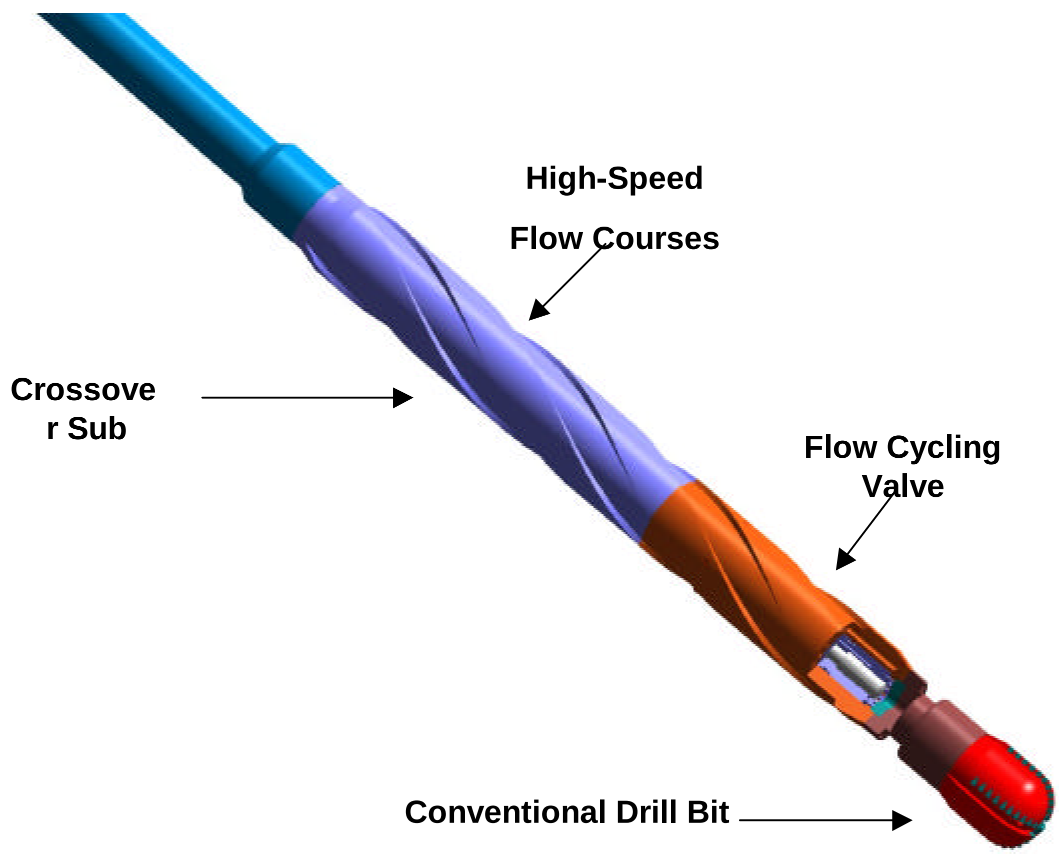

Figure 1. HydroPulse™ drilling system

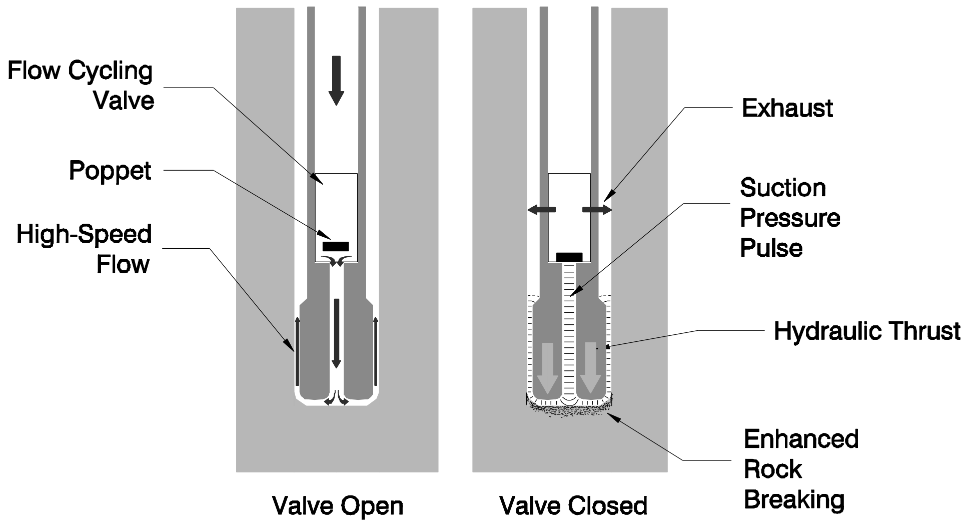

Figure 2. Suction pulse drilling.

The magnitude of the suction pulse can be evaluated by equating the kinetic energy of flow in a closed conduit to the elastic potential energy of the decompressed fluid volume. If the initial flow velocity is v, the magnitude of the water-hammer pressure pulse is

$$\Delta P = v\sqrt{rK_f} \ , \tag{1}$$

where K_f is the bulk modulus of the fluid and r is the density (Trostmann 1996). In water (K_f= 2.4 GPa at 35 MPa), the pressure pulse has an amplitude of about 1.5 MPa per m/s flow velocity. The pressure magnitude increases with the square root of the mud density. Flow velocities of 10 to 20 m/s are common in the flow courses of carbide body drill bits, so pressure pulses of 15 to 30 MPa (2000 - 4000 psi) or more can be generated. The duration of the pressure pulse is determined by the two-way travel time of acoustic waves in the flow conduit. The speed of sound in water is about 1500 m/s so the duration of a pressure pulse in a high-speed flow course with a length of 1 m would be about 1.3 milliseconds.

RESULTS

The Phase I project discussed here involved the development and testing of a small-scale prototype suction pulse valve. This valve was used for a series of pressure drilling tests demonstrating the effect of suction pulses on drilling performance. This section discusses the results of small scale drilling tests.

Prototype Flow Cycling Valve and Test Setup

Figure 3 shows an engineering prototype flow cycling valve designed for a flow rate of 2 x 10^{-4} m^3/s (3.4 gpm). The discharge from this valve is directed through the pressure drilling test stand shown in Figure 4. The flow cycling valve periodically interrupts the flow from the drill to the bit and diverts it to an exhaust port. When the cycling valve poppet is open, flow enters through the drill rod and is discharged through open ports on the bit. The high speed flow is directed through flow courses around the bit into a 1-m long suction pressure line. The intensity of the pressure pulse is related to the flow velocity in the suction pulse line while the pulse duration is related to the length of the line. High pressure is maintained in the pressure vessel by directing the flow from the suction pressure line and cycling valve exhaust through an adjustable choke.

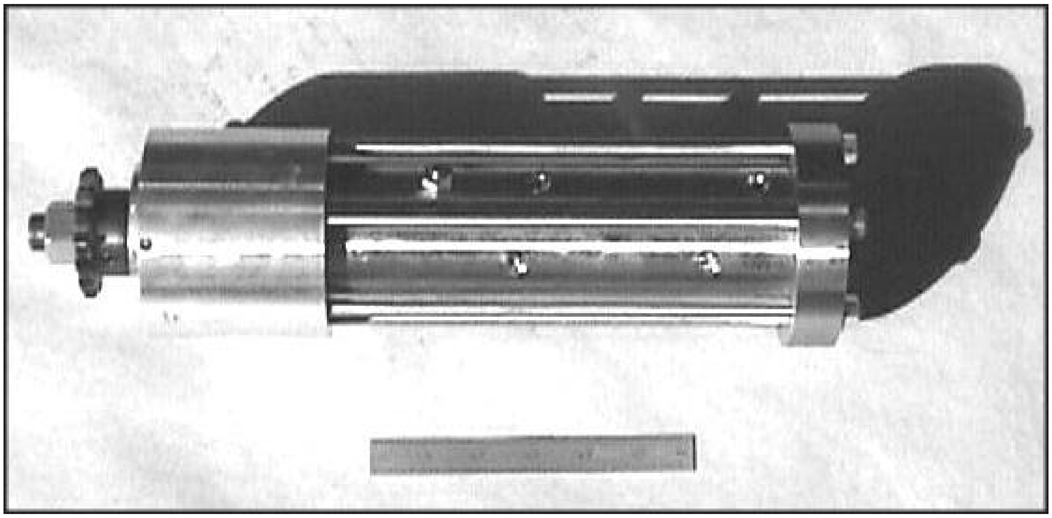

Figure 3. Engineering prototype flow cycling valve - ruler is 150 mm (6").

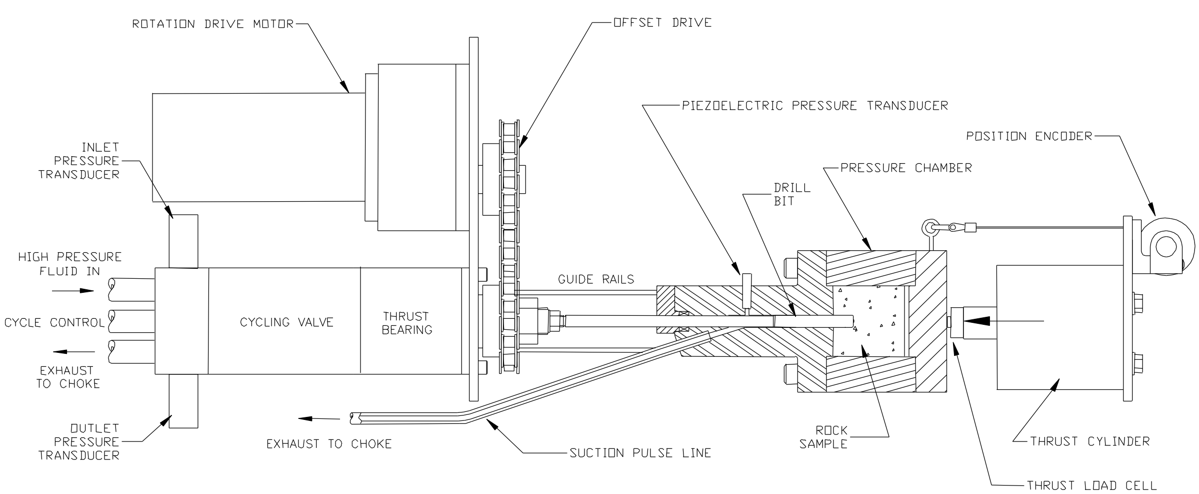

Figure 4. Small-scale pressure drilling test stand layout.

Figure 5 shows an example of a series of suction pressure pulses generated in a borehole in shale by the engineering prototype with a 1 m suction pulse flow line. The pressure pulses occur at a cycle rate of 47 Hz and each pulse has a duration of about 1.3 milliseconds. The hydraulic power associated with each pulse is .75 J and the power level is 35 W in this example. Figure 6 shows the pressure upstream of valve. There are no water hammer pressure spikes upstream of the valve because the flow is never interrupted. This means that this cycling valve could be located downstream of a downhole motor without affecting motor performance.

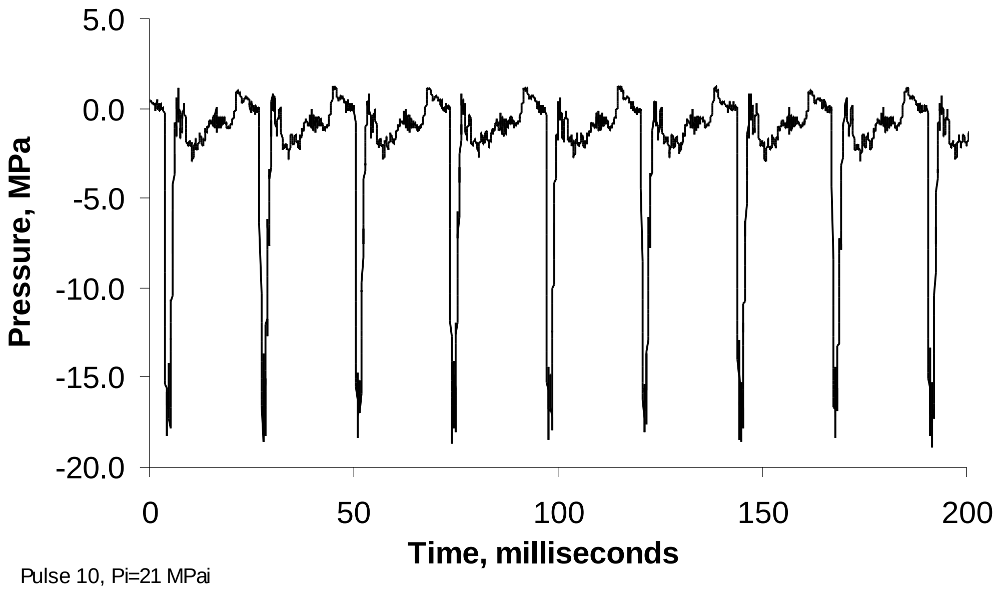

Figure 5. Example of 35 W suction pulse train generated by a flow interruption valve in combination with a high speed flow course. (1000 psi = 6.9 MPa).

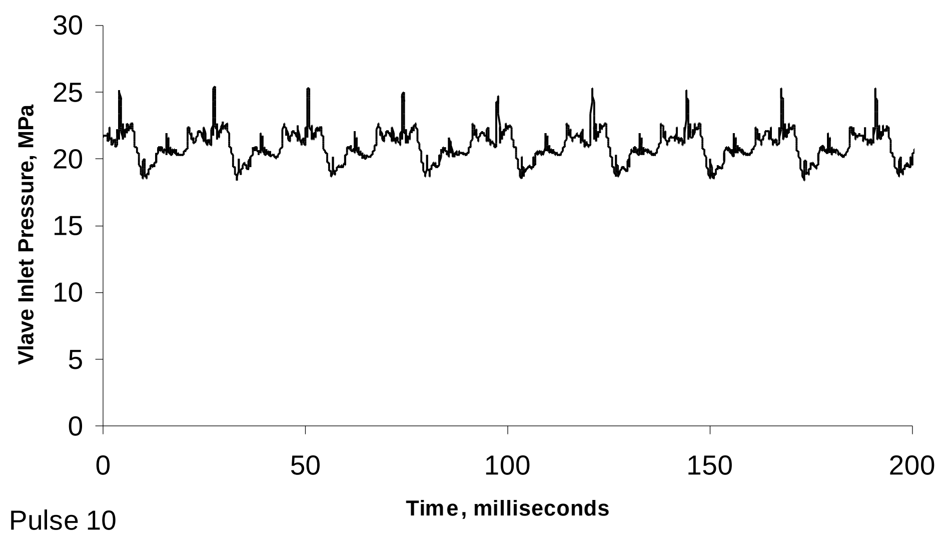

Figure 6. Upstream pulse profile on valve inlet pressure manifold.

The power spectrum of the suction pressure pulse signal is shown in Figure 7. This is the amplitude of the pressure that would be received at a range of 1 m from the source. The pulse energy has strong peaks at the basic cycle frequency and its higher harmonics. The power at 1 kHz is only 20 dB below the peak at 43 Hz indicating that this pulse would provide an intense source of high frequency seismic energy. Despite its tiny size, the power level of this source at harmonics of the repetition frequency is comparable to that of a moderate size airgun array (Dragoset 1990). A 200 mm diameter source would 27 dB higher in power.

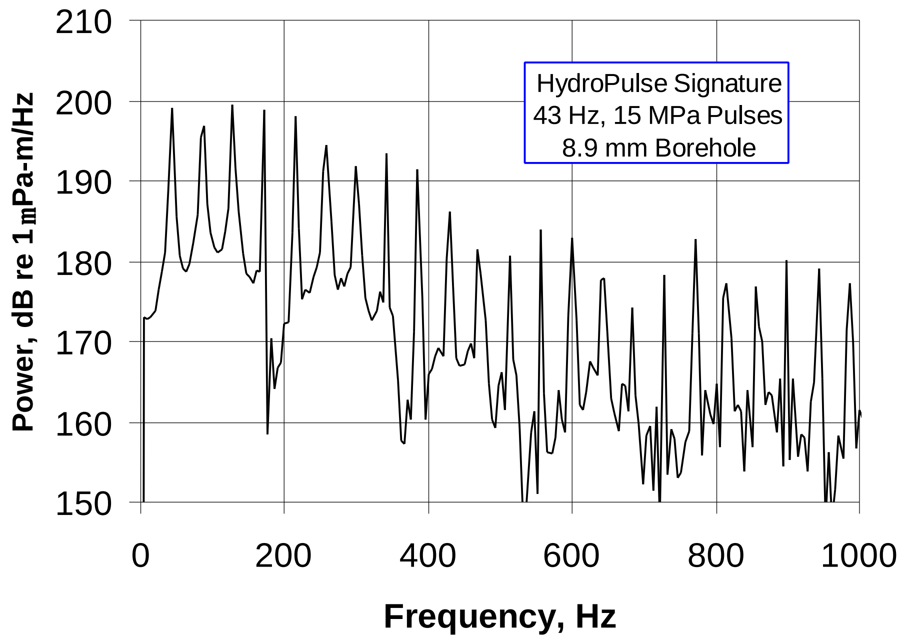

Figure 7. Amplitude spectrum of small scale (35 W) pulse signal (see Figure 5)

Small-Scale Drilling Tests

A series of small-scale drilling experiments were carried out to demonstrate the concept of suction pulse drilling. These experiments involved rotary drilling with a small, 8.7 mm (.343") diameter drill into a pressurized rock sample. Drill bits with and without mechanical cutting elements were used. Drilling tests were carried out with and without the application of underbalance pressure pulses in order to allow a direct observation of the effect. As shown in Figure 8, the application of suction pressure pulses causes a sharp increase in penetration rate.

Figure 9 shows a carbide bit that was fabricated by grinding a 20 degree negative backrake on the carbide. The cutter edge was ground to a 90 degree angle to provide clearance on the face. The backrake cutter bit was used to drill two samples of Mancos Shale. Tests were carried out at two thrust levels. When suction pulses are applied at zero thrust, the penetration rate of the backrake cutter is essentially the same as with 200 N thrust. The drilling rate with 200 N thrust shows a step increase by a factor of four at around 10 MPa suction pulse pressure.

A similar test was carried out in Colton Sandstone at relatively low thrust. The application of 16 MPa suction pulses causes the penetration rate to triple.

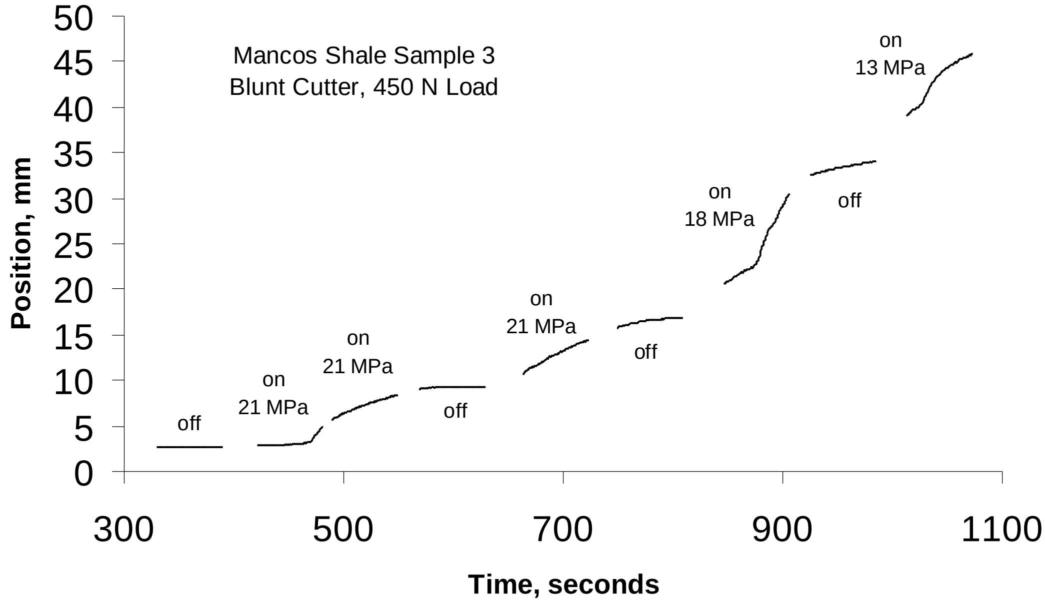

Figure 8. Example test record showing bit penetration with cycling on and off.

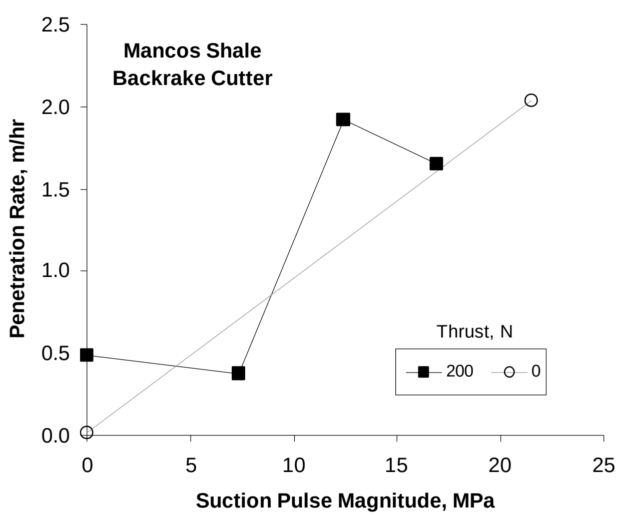

Figure 9. Mancos Shale drilling with backrake cutter at 60 rpm, 21 MPa ambient pressure.

An indentor bit with a 120 degree included angle carbide cutter was used to carry out suction pulse drilling tests in Sierra White Granite (Figure 10). The application of 9 MPa suction pulses at a frequency of 20 Hz caused the penetration rate to triple in the granite sample.

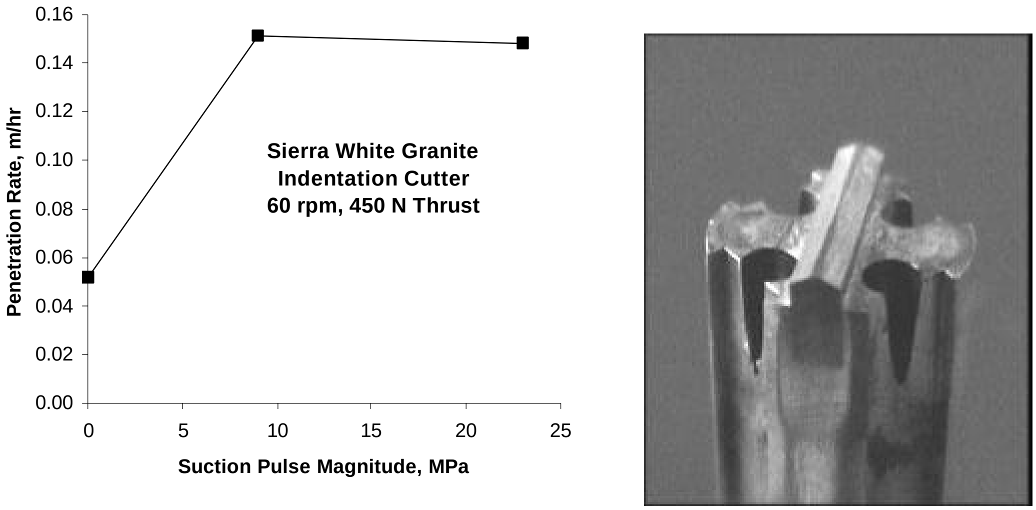

Figure 10. Indentor bit drilling rates in Sierra White Granite. Ambient pressure = 23 MPa.

The drilling rate data obtained during the feasibility study are summarized in Table 1 All of the drilling tests in shale, sandstone and granite indicated a significant increase rate of penetration as a result of the application of suction pulses. The increased penetration rate was observed at pulse magnitudes of around 10 MPa and a frequency of 20 Hz in Mancos Shale. Application of a 10 MPa suction pressure pulse, causes the mechanical load to increase by 250 N for about 1.5 milliseconds. The pulses do not have the short duration or high amplitude characteristic of an impact. The pulse rate is 20 Hz so the time-averaged thrust increase is only 8N. The increased thrust can only account for a small part of the observed effect on drilling rate. An analysis of suction pulse propagation in rock has shown that these pulses will induce effective tensile stresses in the rock that are comparable or greater than the tensile strength of the rock (Kollé 1998). We conclude that the increased drilling rate results from the combined effects of effective tensile stresses and mechanical indentation.

Table 1. Drilling rate summary; all data at 60 rpm, 21 MPa ambient pressure.

Bit	Rock	Thrust N	No Cycling ROP m/hr	Cycling ROP m/hr	ROP Ratio	Cycling Pressure MPa
Blunt	Mancos Shale	450	0.05	0.3	6	12
	Colton Sandstone	450	0.17	0.34	2	18
Backrake	Mancos Shale	0	0	2.1	∞	22
		200	0.5	2.0	4	7
	Colton Sandstone	40	1.2	4.6	4	16
Indentation	Granite	450	.05	.15	3	9

APPLICATIONS

The Phase I work described here has demonstrated the feasibility of a suction pulse generator and its application to drilling. This system would significantly enhance the rate of penetration and reduce the cost of deep drilling. The technology demonstrated here has significant other applications including horizontal drilling, seismic-while-drilling and workovers in open hole and tubulars.

Drilling

The primary application of the HydroPulse™ system is faster drilling in deep formations. The suction pulses will reduce the drilling strength of formations such as shale that become strong and highly plastic in deep boreholes. The pulses will also reduce formation balling and bit balling by overcoming the differential pressures that cause formations to stick together. The pulse technique provides the advantages of underbalanced drilling at the bit while allowing formation pressure control above the bit.

Seismic

Seismic investigation provides an important tool for characterizing oil and gas reservoirs. Seismic work is normally carried out separately from drilling although seismic analysis of the signal from a roller cone bit has been used for velocity profiling. The suction pulse generator provides an intense, periodic acoustic signal that can be used for seismic-while-drilling. The suction pulse drilling system discussed above would generates a pulse power of 7 kW with significant energy at frequencies greater than 1 kHz compared to peak frequencies of around 10 Hz for drill bit seismic. In this application a seismic receiver would be located on the surface, in a parallel borehole or on the drill string above the bit. Seismic interpretations of formation properties may be used to locate the bit and oil or gas bearing formations. Reflections of pulses from formations ahead of the bit can be used for high-resolution imaging while drilling. The intense signals generated by the suction pulse system are particularly well-suited for determining pore pressures in the formation ahead of the bit. High formation pore pressure or the presence of gas causes strong attenuation of seismic signals (Mavko and Nur 1979). Drill bit seismic cannot be used for attenuation measurements because the source signals are not well-characterized. Knowledge of formation pore pressure provides enhanced safety during drilling particularly in deep water drilling and in gas-pressurized formations.

Formation Damage Removal

The suction pressures generated by the this tool could also be used to remove fine-grained materials which can clog the pores of oil and gas producing zones. Formation damage commonly occurs during overbalanced drilling because fine-grained materials are forced into the formation by the differential pressure. Near-wellbore formations may also become blocked during drilling or production by fine-grained minerals and other materials. The suction pressure pulses produced by the invention will remove fines from the formation in order to enhance oil and gas production rates. The pulses could also be used to clean out perforations following casing penetration with shaped charges.

FUTURE ACTIVITIES

Tempress Technologies is now engaged in the development of a full-scale HydroPulse™ valve that is designed to operate on drilling mud. The valve design shown in Figure 11 would fit into a 150-mm diameter (6") subassembly and is designed for full scale suction pulse drilling operations. The valve circuit is similar to engineering prototype shown in Figure 2. This valve will operate at 85% volumetric efficiency – that is 15% of the flow is used to actuate the valve and is exhausted.

Specifications for a 150-mm diameter (6") HydroPulse™ drilling system are provided in Table 2. At a flow rate of 300 gpm the cycling valve would operate at 60 Hz. The cycling frequency and suction pulse magnitude are proportional to flow rate. Intermediate scale systems suited for operation on coiled tubing are also possible. The pulse power level on the face of a 200 mm diameter bit would be 165 kW/m^2 (0.14 HSI). The subassembly would be installed above a conventional PDC or roller cone bit that is equipped with jet nozzles. Surge and swab pressures were calculated as a function of mud weight and viscosity using a turbulent Bingham fluid model (Monicard 1982). The surge pressures are insignificant compared to. normal pressure fluctuations during tripping with conventional drilling tools (Bourgoyne et al. 1986).

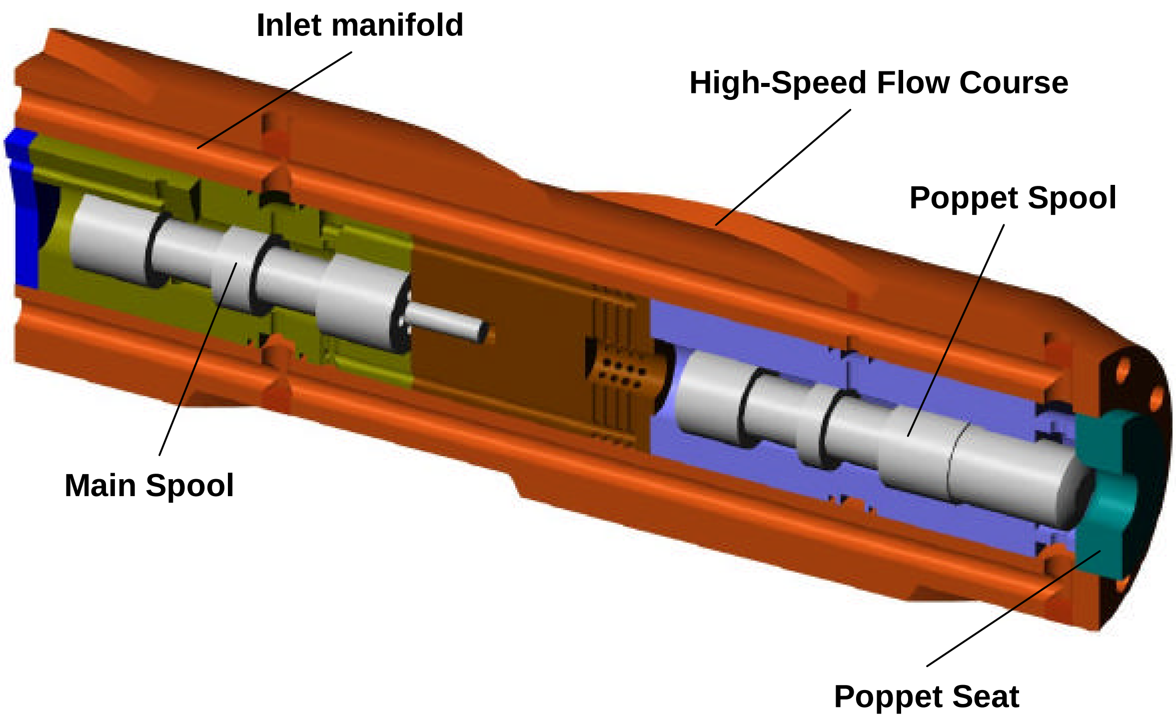

Figure 11. Full-scale HydroPulse™ cycling valve assembly configured for borehole applications.

Table 2. Specifications for a 150-mm (6”) HydroPulse™ system.

Cycling Valve Diameter	150 mm (6”)
Cycling Valve Length	600 mm (24”)
Volumetric Efficiency	85%
Flow Course Length	1.5 m (60”)
Flow Rate	.019 m^3/s (300 gpm)
Pulse Frequency	60 Hz
Flow Course Area	.0032 m^2 (5.0 in^2)
Flow Velocity	6 m/s (20 ft/s)
Pulse Amplitude	9 MPa (1300 psi)
Pulse Power	5.2 kW (7 hp)
Hydraulic Thrust Force on 200 mm (7-7/8”) Bit	283 kN (64,000 lbf)
Maximum Hydraulic Liftoff (11 ppg, 100 cp mud)	< 2 kN (400 lbf)
Surge Pressure (tripping @ 1m/s in 11 ppg, 100 cp mud)	< 140 kPa (21 psi)

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